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https://doi.org/10.1149/2.0061708jes


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Physical and Electrochemical Properties of Some Phosphonium-Based Ionic Liquids and the Performance of Their Electrolytes in Lithium-Ion Batteries

Nuha Salem, Serguei Zavorine, Donato Nucciaronne, Kristina Whitbread, Mike Moser, and Yaser Abu-Lebdeh

aNational Research Council of Canada, Ottawa, Ontario K1A 0R6, Canada
bSolvay, Niagara Falls, Ontario L2E 6S5, Canada

In this work, three ionic liquids with two different cations and two different anions: trimethyl propyl phosphonium bis-fluorosulfonyl imide (P1113FSI), trimethyl isobutyl phosphonium bis-fluorosulfonyl imide (P1144FSI) and trimethyl isobutyl phosphonium bis-trifluoromethylsulfonyl imide (P1114TFSI) have been characterized and evaluated as electrolytes in lithium ion half-cells. It is found that ionic liquids with FSI− anion have superior properties over their TFSI− counterparts and those with the smaller cation, P1113, have better conductivity and viscosity. The two ionic liquids with FSI anion, P1113FSI and P1144FSI, are liquid at room temperature and show high conductivities and low viscosities, reaching 10.0 mS/cm and 30 cP at room temperature for P1113FSI. They also exhibit electrochemical windows higher than 5 V and thermal stability exceeding 300°C. Mixing the ionic liquids with 0.5 M LiPF6 increases viscosities, lowers conductivities but improves electrochemical cathodic stability. The electrolyte mixtures have been evaluated in graphite/Li half cells, Li/LiFePO4 and Li/LiMn2O4 cathode at C/12 for 100 cycles and at different rates: C/6, C/3, C and 2C for rate capabilities. Battery testing shows that unlike their TFSI− counterparts both ionic liquids with FSI− anion perform well with graphite anode and LiFePO4 cathode but fail with the higher voltage LiMn2O4 cathode.

Experimental

Ionic liquids.—Ionic liquids were provided by Solvay with purity of >96% for P1113FSI and >99% for P1144FSI and P1114TFSI and were additionally dried overnight in vacuum oven at 80°C before they were characterized and used in battery testing.

Water content of <50 ppm was measured using Karl-Fischer MCI moisture meter, model CA-05 from Mitsubishi.

*E-mail: Yaser.Abu-Lebdeh@nrc.gc.ca; Serguei.Zavorine@solvay.com

Scheme 1. Chemical structure of the three phosphonium-based ionic liquids used in this work.
Thermal and electrochemical characterization.—Differential scanning calorimetry (DSC) analysis was recorded using a TA Instruments DSC Q2000. All samples were sealed in aluminum pans inside an Ar-filled glove box and then scanned from −90 to 150 °C at a rate of 5 °C/min under helium gas. Conductivity measurements were performed using the AC impedance spectroscopy technique where the electrolyte solutions were poured into a two-platinum-electrode conductivity cell with a cell constant of 1 cm⁻¹. The frequency was swept between 1 kHz and 0.1 Hz using Princeton Applied Research PAR 263A potentiostat coupled with a Solartron frequency response analyzer FRA 1255B. The temperature was varied between −20 and 100 °C allowing 20 min for thermal equilibration. Linear sweep voltammograms were conducted using a platinum microelectrode (25 μm) and a silver wire as a counter and reference electrode. These measurements were also done using the Princeton Applied Research PAR 263A potentiostat at room temperature with a scan rate of 10 mV/s.

Viscosity.—Viscosity measurements were recorded using a CANNON-Ubbelohde viscometer. This method requires a sample size of 7–9 ml and for this reason the viscosity of 0.5 M LiPF₆ P₃₆F₆ was not determined due to insufficient amount.

Half-cell assembly.—Battery investigations were carried out with coin-type cells. Cathode was made from a slurry containing 80% LiFePO₄ (in-house synthesized) or LiMnₓNi₉₋ₓO₂ (NEI corporation), 5% KS-4 graphite, 5% Super-P carbon and 10% PVDF binder in NMP and anode was made of 85% MCMB graphite, 5% Super-P carbon and 10% PVDF binder in NMP. The cathode slurry was casted onto an aluminum foil while the anode slurry was coated on copper foil then dried overnight at 80 °C in a vacuum oven. Electrode discs of 12.7 mm diameter were punched from the coated foil and pressed at 0.5 ton pressure. The cells were assembled in an Ar-filled dry box at room temperature using Li as anode and 2 layers of microporous polypropylene separators (Celgard 3501). Cell performance was evaluated by galvanostatic experiments carried out on a multichannel Arbin battery cycler at 30 °C. Li/LiFePO₄ and MCMB/Li half cells were cycled at 2.5–4.2 V and 0.005–1.5 V respectively. The cells were charged and discharged at constant current density of C/12 for long term cycling and at C/6, C/3, C and 2C (10 cycles each) for rate capabilities.

Results and Discussion
Characterization of ionic liquids.—Differential scanning calorimetry.—DSC scans of the three neat ionic liquids and their corresponding electrolyte solutions with LiPF₆ salt were recorded from −90 °C to 150 °C as seen in Figure 1. It can be seen that the melting points (m.p.) of the three liquid salts, P1113FSI, P1114FSI and P1114TFSI in their neat form were: 2.4 °C, 12.5 °C (liquids at room temperature) and 43 °C (solid at room temperature), respectively. The first two values were in agreement with Tsunashima et al. and Girard et al. while the last value was in agreement with Hilder et al. As expected, the TFSI−-based ILs have higher m.p. than the FSI−-based analogs. These values illustrate the crucial effect of the size and shape of the cation in combination with the size and shape of the anion on the packing and crystallization behavior of the salt. It was also observed that P1113FSI was the only ionic liquid that showed extra peaks below melting that can be attributed to the presence of other phases/crystalline structures of lower melting points or due to a solid-solid transition corresponding to a regular crystalline to plastic crystalline phase. When LiPF₆ salt was added (to the molten state in case of P1114TFSI), the m.p. was expectedly shifted to much lower values: <−90 °C for 0.5 M LiPF₆ P1113FSI, 0.5 °C for 0.5 M LiPF₆ P1114FSI and 17–23 °C for 0.5 M LiPF₆ P1114TFSI. The negative shift in the melting point upon adding the lithium salt is expected and usually attributed to the disruptive effect the salt has on the packing of ionic liquid molecules due to the new strong ion-ion interactions between the ionic liquid and the lithium salt ions.

Viscosity and conductivity.—The viscosity of neat P1113FSI and P1114FSI liquids were measured at room temperature and found to be 30 and 40 cP, respectively, while the viscosity of P1114TFSI was not determined because it’s a solid state at room temperature. These values are in agreement with the values determined by Tsunashima et al. and Girard et al. The viscosity of ionic liquids is known to depend, among other things, on the molecular frictional forces that are governed by the size. It is known that molecules with high molecular weight show higher friction along with slow diffusion and therefore lead to higher viscosity. This explains the increase of viscosity as the cation becomes bigger (P1114TFSI > P1113FSI). Upon the addition of the 0.5 M LiPF₆ to P1114FSI, the viscosity increased to 91 cP due to the introduction of much stronger ion-ion interactions, e.g. FSI− and Li⁺. The viscosity of 0.5 M LiPF₆ P1113FSI, which was not determined due to insufficient amount of material, was also visibly higher (qualitatively) than the neat P1113FSI but lower than 0.5 M LiPF₆ P1114FSI, as expected. To compare the effect of the anion on the viscosity of the electrolyte, 0.5 M LiPF₆ P1114TFSI was prepared by adding lithium salt to the molten ionic liquid. The electrolyte did not solidify upon cooling, as evident from DSC, which showed a melting point just below room temperature. This is attributed, as mentioned above, to the disruption of the interaction between P1114 cation and TFSI− anion due to the new interaction with the smaller Li⁺ cation from LiPF₆. The viscosity of 0.5 M LiPF₆ P1114TFSI, however, was high at 269 cP. Although the comparison to the neat P1114TFSI viscosity is not possible at room temperature, it can be seen here that the ion-ion interaction between TFSI− and Li⁺ is much stronger than FSI− and Li⁺. This explains the much higher viscosity of the LiPF₆ electrolyte of the TFSI− ionic liquid compared to its FSI− counterpart.

The ionic conductivities of the neat ionic liquids and their electrolytes with LiPF₆ were measured over a temperature range from −20 to 100 °C (40 to 100 °C for P1114TFSI) as shown in Figure 2. It was found that for neat ionic liquids the trend in conductivity at any given temperature followed, inversely, the trend in viscosity as follows: P1113FSI > P1114FSI > P1114TFSI. It was also found that the conductivity increased as a function of temperature reaching 37.0 mS/cm, 27.0 mS/cm and 15.1 mS/cm at 100 °C, respectively. The conductivity-temperature curve of P1114FSI showed a large drop in the conductivity at −20 °C due to freezing at 12.5 °C. On the other hand, P1113FSI showed no such discontinuities due to, as shown by DSC, its partial melting at temperatures that extended to −50 °C. It should also be noted that the value of the conductivity for P1114FSI (10 mS/cm) is higher than the one reported by Tsunashima et al. (7.1 mS/cm) and we are currently unable to discern the reasons for such a difference.
The addition of 0.5 M LiPF$_6$ decreased the conductivities due to the increased viscosity as expected with a trend matching the neat ionic liquids: 0.5 M LiPF$_6$ in P$_{1113}$FSI > 0.5 M LiPF$_6$ in P$_{1114}$FSI > 0.5 M LiPF$_6$ in P$_{1114}$TFSI. Room temperature conductivities of 4.8 mS/cm, 3.5 mS/cm and 0.55 mS/cm for 0.5 M LiPF$_6$ in P$_{1111}$FSI, P$_{1114}$FSI and P$_{1114}$TFSI, respectively, were lower than those for conventional carbonate-based electrolytes which are usually > 8 mS/cm. The values for the two FSI$^-$ ionic liquid electrolytes, although lower than conventional electrolytes, are considered high in comparison to other ionic liquids with different cation/anion combinations. The focus on phosphonium-based ionic liquids has recently increased due to the fact that they usually exhibit lower viscosities and higher conductivities compared to their ammonium-based ionic liquid counterparts. For example, P$_{1235}$TFSI was found to have a viscosity of 88 mPa.s while its ammonium counterpart, N$_{1235}$TFSI has a viscosity of 172 mPa.s. It should be noted, however, that P$_{1114}$TFSI is a solid with m.p. of 40–43°C [17, 19, this study] while N$_{1114}$TFSI is a liquid with the viscosity of 72 cP and the conductivity of 3.3 mS/cm.

It is conventional to say that ionic conductivity is inversely controlled by viscosity, but although this statement is empirically correct it is not from the theoretical point of view; as in essence both the conductivity and viscosity are controlled by similar forces. The addition of a salt to an ionic liquid can only increase the short-range, ion-coulombic interactions but there is evidence that, similar to other systems, the increased viscosity as expected with a trend matching the neat ionic liquids could be responsible for ion transport.

Linear sweep voltammetry.—The electrochemical stability of the ILs was evaluated using linear sweep voltammetry and the results are shown in Figure 3. The anodic voltammetry sweep of the neat ionic liquids P$_{1113}$FSI and P$_{1114}$FSI showed an oxidation onset at 2.42 V and 2.53 V (vs Ag/Ag$^+$), respectively, while cathodic voltammetry sweep showed an onset of reduction at −2.63 V and −2.9 V vs Ag/Ag$^+$ respectively. These values correspond to an electrochemical stability window of 5.05 V for P$_{1113}$FSI and 5.43 V for P$_{1114}$FSI. Our results are in a good agreement with Tsunashima et al. who found that P$_{1113}$FSI has a potential window of ~5.0 V and Girard et al. who found that P$_{1114}$FSI has a potential window of 5.5 V with a slightly different oxidation and reduction onset in both cases. These slight differences could simply be attributed to a shift in potential due to the use of different electrodes and possibly due to different impurity profiles originating from two different synthetic methods. The higher cathodic stability of P$_{1114}$FSI is attributed to the higher cathodic stability of the P$_{1114}$ cation due to the presence of the more electron donating, branched isobutyl group in comparison with linear n-propyl group.

Upon the addition of 0.5 M LiPF$_6$, the cathodic stability was improved for P$_{1114}$FSI and P$_{1114}$FSI by 1.2 V and 0.9 V, respectively, resulting in an electrochemical stability window of 6.25 V for 0.5 M LiPF$_6$ P$_{1113}$FSI and 6.33 V for 0.5 M LiPF$_6$ P$_{1114}$FSI. This improvement is likely the result of the passivation caused by the reduction product of PF$_6^−$. It was possible to run the linear sweep of 0.5 M LiPF$_6$ P$_{1114}$TFSI since the mixture was liquid and was found to have a reduction onset of −3.8 V and an oxidation onset of 2.5 V vs Ag/Ag$^+$. The slightly higher oxidation potential compared to 2.4 V for 0.5 M LiPF$_6$ P$_{1113}$FSI vs Ag/Ag$^+$ is attributed to the better stability of TFSI$^−$ toward oxidation than FSI$^−$ due to higher charge delocalization. The scans for the FSI$^−$ ionic liquids with LiPF$_6$ show small reduction peaks in the potential range from −0.5 V to −1 V on the cathodic run, which can be attributed to impurities such as residual water that may have been introduced by the lithium salt.

Battery performance.—Graphite/Li half cells.—Electrolyte mixtures based on each of the ionic liquids with 0.5 M LiPF$_6$ were prepared and used for battery testing. 0.5 M LiPF$_6$ was chosen to ensure complete solubility and maintain acceptable conductivity by keeping viscosity as low as possible. LiPF$_6$ also is significantly less expensive than LiTFSI and LiTFSI salts. Figure 4a shows the cycling performance of MCMBl/Li half cells formulated with these electrolytes and with 1 M LiPF$_6$ EC/DMC 1:1 conventional electrolyte for comparison. Both 0.5 M LiPF$_6$ P$_{1113}$FSI and 0.5 M LiPF$_6$ P$_{1114}$FSI produced capacities that are comparable to the conventional electrolyte with slightly higher initial discharge capacities of 363 mAh/g and 350 mAh/g, respectively, compared to 340 mAh/g for 1 M LiPF$_6$ EC/DMC 1:1 (v/v). The irreversible capacities, ~30 mAh/g, were also comparable with conventional electrolyte. The capacities stabilized at 325 mAh/g for both electrolytes with no capacity loss for 0.5 M LiPF$_6$ P$_{1113}$FSI and 7% capacity loss for 0.5 M LiPF$_6$ P$_{1114}$FSI over 100
Figure 4. (a) Discharge capacities of MCMB graphite/Li half-cells made with ionic liquid and conventional electrolytes at C/12. Open symbols are corresponding coulombic efficiencies. (b-d) Corresponding cycling performance curves at 1st and 10th cycles. (c) Corresponding cycling performance curves of 0.5 M LiPF$_6$ P$_{1114}$FSI at 1st and 10th cycles. (d) Corresponding cycling performance curves of 0.5 M LiPF$_6$ P$_{1114}$TFSI at 1st and 10th cycles. P$_{1114}$FSI and P$_{1114}$TFSI refer to P$_{1114}$FSI and P$_{1114}$TFSI in the text.
cycles. The electrolyte made with 0.5 M LiPF<sub>6</sub> P<sub>1113</sub>TFSI failed to cycle with MCMB/Li giving initial capacity of only 55 mAh/g which dropped to almost zero in the subsequent cycles. The inability of 0.5 M LiPF<sub>6</sub> P<sub>1114</sub>TFSI electrolyte mixture to give any capacity is attributed to its failure to form a functioning SEI layer as evidenced by the discharge/charge curve, as discussed below. The efficiencies of the two FSI electrolytes were excellent approaching 100% which indicate minimal energy loss during the charge-discharge cycling process. Charge-discharge curves of the 1<sup>st</sup> and 10<sup>th</sup> cycle for these half cells are shown in Figure 4b–4d. It can be seen from these curves that an SEI layer starts to form in the first cycle at 1 V for 0.5 M LiPF<sub>6</sub> P<sub>1113</sub>FSI and 0.65 V for 0.5 M LiPF<sub>6</sub> P<sub>1114</sub>FSI due to the decomposition of the electrolyte. This decomposition disappears in the subsequent cycles indicating the formation of a stable SEI layer. In the case of 0.5 M LiPF<sub>6</sub> P<sub>1114</sub>TFSI, this step is much more pronounced, which indicates a higher degree of decomposition represented by a reduction activity that can be seen at −3.5 V in the linear sweep (Figure 3). This decomposition possibly leads to a thick, insulating SEI layer resulting in the irreversible intercalation/de-intercalation process and the poorer performance.

Rate capabilities at faster charge-discharge rates of C/6, C/3, C and 2C were also investigated as seen in Figure 5. The performance of 0.5 M LiPF<sub>6</sub> P<sub>1113</sub>FSI was better than 0.5 M LiPF<sub>6</sub> P<sub>1114</sub>FSI at C/3, C and 2C. Capacities were reasonable up to C/3: 190 mAh/g and 149 mAh/g for 0.5 M LiPF<sub>6</sub> P<sub>1113</sub>FSI and 0.5 M LiPF<sub>6</sub> P<sub>1114</sub>FSI, respectively, but faded significantly at higher rates to <50 mAh/g. In general, the capacities at rates > C/6 were higher for conventional electrolyte than both ionic liquids. Lower rate capability behavior could be attributed to the lower conductivity of the ionic liquid solutions compared to the conventional electrolyte and most probably lower Li<sup>+</sup> transport numbers. The recovery at C/12 was however better for the ionic liquids compared to the conventional electrolyte.

Li/LiFePO<sub>4</sub> half cells.—Li/LiFePO<sub>4</sub> half-cells were made using the same electrolytes used in graphite/Li half cells. The cells gave an initial discharge capacity of 124 mAh/g and 110 mAh/g for 0.5 M LiPF<sub>6</sub> P<sub>1113</sub>FSI and 0.5 M LiPF<sub>6</sub> P<sub>1114</sub>FSI, respectively, which are lower than the one obtained with 1 M LiPF<sub>6</sub> EC/DEC 3:7 (v/v) conventional electrolyte (150 mAh/g) (Figure 6a). The capacities of the two electrolytes however reached maximum after 20 cycles and stabilized for the remaining 100 cycles. These capacities were slightly better for 0.5 M LiPF<sub>6</sub> P<sub>1113</sub>FSI (152 mAh/g) compared to both 0.5 M LiPF<sub>6</sub> P<sub>1114</sub>FSI (147 mAh/g) and the conventional electrolyte (148 mAh/g). Both conventional and 0.5 M LiPF<sub>6</sub> P<sub>1113</sub>FSI electrolytes lost only 4% of capacity over 100 cycles while 0.5 M LiPF<sub>6</sub> P<sub>1114</sub>FSI lost 11% of its capacity over 100 cycles. The coulombic efficiencies were irregular and in some cases poor reaching values as low as 92% for the FSI ionic liquid electrolytes for the first 12 cycles which then improved to ~99% for the duration of the cycling. This poor efficiency could be attributed to higher polarization at the electrolyte-electrode interface due to slower diffusion in the electrolyte as a result of the higher viscosity exacerbated by the slow Li diffusion at the LiFePO<sub>4</sub>/LiFePO<sub>4</sub> two-phase region of the LFP electrode. As expected, half-cells made with 0.5 M LiPF<sub>6</sub> P<sub>1114</sub>TFSI gave poor performance with initial capacities of only 85 mAh/g, which faded sharply to almost zero after 20 cycles. Charge-discharge curves of the 1<sup>st</sup> and 10<sup>th</sup> cycle for these half cells are shown in Figure 6b–6d. The cell with the FSI ionic liquids shows a plateau at 3.45 V corresponding to Fe<sup>2+</xFE<sup>3+</sup> redox couple reaction associated with lithium ion intercalation/de-intercalation with an irreversible capacity of 27 mAh/g and 39 mAh/g for 0.5 M LiPF<sub>6</sub> P<sub>1113</sub>FSI and 0.5 M LiPF<sub>6</sub> P<sub>1114</sub>FSI in the first cycle respectively. After 10 cycles, the cells had excellent coulombic efficiency with minimal irreversible capacity. The plateau for 0.5 M LiPF<sub>6</sub> P<sub>1114</sub>TFSI occurs at higher voltage of 3.8 V indicating higher polarization due to higher viscosity, as discussed above. High irreversible capacity in the first cycle and poor cycling in the subsequent cycles can also be seen for this electrolyte.

Similar to graphite/Li half cells, the rate capabilities were evaluated by performing 10 cycles at C/6, C/3, C and 2C followed by recovery cycles at C/12, taking into account that 1 C rate for the LiLFP cell corresponds to ~ C/3 for the graphite/Li cell. Both the FSI ionic liquid electrolytes behaved in a similar manner, as shown in Figure 7. The capacities at C/6 and C/3 were very good for electrolytes, 145 mAh/g and 140 mAh/g respectively, being higher than for the conventional

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**Figure 5.** Rate capabilities of MCMB graphite/Li half-cells made with ionic liquid and conventional electrolytes at C/12, C/6, C/3, C and 2C. P<sub>1114</sub>FSI refers to P<sub>1114</sub>FSI in the text.
Figure 6. (a) Discharge capacities of Li/LFP half-cells made with ionic liquid and conventional electrolytes at C/12. Open symbols are corresponding coulombic efficiencies. (b) Corresponding cycling performance curves of 0.5 M LiPF$_6$ P$_{1114}$FSI at 1$^{\text{st}}$ and 10$^{\text{th}}$ cycles. (c) Corresponding cycling performance curves of 0.5 M LiPF$_6$ P$_{1114}$TFSI at 1$^{\text{st}}$ and 10$^{\text{th}}$ cycles. (d) Corresponding cycling performance curves of 0.5 M LiPF$_6$ P$_{1114}$TFSI at 1$^{\text{st}}$ and 10$^{\text{th}}$ cycles. P$_{1114}$FSI and P$_{1114}$TFSI refer to P$_{1114}$FSI and P$_{1114}$TFSI in the text.
electrolyte by ~15 mAh/g. The enhanced performance of the FSI−
ionic liquid electrolytes compared to conventional electrolyte could be
attributed to the ability of the ionic liquids to make lithium ions more
available for interaction with the cathode material. The performance
was still better than conventional electrolyte at 1 C rate while at 2C, 0.5
M LiPF6, P1114FSI gave lower capacities than 0.5 M LiPF6, P1113FSI
and 1 M LiPF6, EC/DEC 3:7 (v/v). Half-cell made with 0.5 M LiPF6
P1113FSI recovered 100% of its original capacity at C/12 while both
0.5 M LiPF6, P1114FSI and 1 M LiPF6, EC/DEC 3:7 (v/v) suffered 7%
capacity loss.

Li/LiMn1.5Ni0.5O4 half cells.—It was anticipated from the elec-
trochemical stability window that the ionic liquids of this study
should be a successful candidate for ~5 V high voltage cathode
LiMn1.5Ni0.5O4, LMNO, cathode. Thus, an attempt was made to cy-
cle Li/LiMn1.5Ni0.5O4 with the ionic liquid electrolytes of this study.
However, Li/LMNO half cells formulated with 0.5 M LiPF6, P1113FSI,
0.5 M LiPF6, P1114FSI and 0.5 M LiPF6, P1114TFSI failed to produce
any capacity (Figure 8). This is possibly due to the reactivity of the
ionic liquid electrolytes toward the active metal cations at the sur-
fcase of LiMn1.5Ni0.5O4. This could lead to chemical side-reactions

(a) Discharge capacities of Li/LMNO half-cells made with ionic liquid and conventional electrolytes at C/12. Open symbols are corresponding coulombic
efficiencies. P1114FSI and P1114TFSI refer to P1114FSI and P1114TFSI in the text.
that do not give a stable Cathode-Electrolyte-Interface, (CEI), passivation layer such as in the case of carbonate electrolytes, which in turn alters the cathode performance. It was previously found by our group that ionic liquid-based electrolytes can be successfully cycled with LMNO cathodes only if ethylene carbonate (EC) is added as co-solvent, possibly due to the formation of stable CEI layer on the surface of the electrode in the presence of EC and linear carbonates that protect the electrode from reacting with the ionic liquids. It is widely accepted now that EC, when present with other solvents, that do not give a stable Cathode-Electrolyte-Interface, (CEI), passivation layer such as LiFSI or LiTFSI instead of LiPF$_6$, Gao et al. used LiTFSI salt with an ammonium based ionic liquid to successfully cycle Li/LMNO half-cell. The use of additives is also a common approach; in some cases ionic liquids were shown to improve cyclability of LMNO.

Conclusions

Some ionic liquids based on phosphonium cations were characterized and tested in lithium ion batteries. It was found that the size/shape of the cation and the variation in the counter anion have a significant effect on the physical and electrochemical properties and as a result battery performance. The ionic liquid with smaller cation, P$_{1133}$, was less viscous and more conductive. When combined with FSI anion it gave the best thermal, physical and electrochemical properties and the best battery performance of the ILs tested. The formulated electrolytes of the ionic liquids with 0.5 M LiPF$_6$, without having any co-solvent or additive, exhibited higher viscosities, lower conductivities and wide electrochemical windows (>6 V). The electrolytes of the ionic liquid performed well with the common graphite anode in MCMB/Li half cell and common cathode LiFePO$_4$ in a Li/LFP half cell and was comparable with conventional electrolytes at slow rates, C/12 and C/6 for MCMB/Li and at slow and fast rates for Li/LFP producing ~320 mA/h and 150 mA/h at C/12 for MCMB/Li and Li/LFP, respectively. The same electrolytes however did not perform well with the high voltage cathode (~5 V) LiMn$_2$NiO$_4$ in Li/LMNO half cells possibly due to the inability of ionic liquid electrolytes to form a passivation (CEI) layer at LMNO surface.

Acknowledgments

The authors thank the Office of Energy Research and Development at Natural Resources Canada and Solvay for financial support.

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